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Geomorphology of the central Po Plain, Northern Italy

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ABSTRACT
A micro-relief map (1:90,000 scale) and a geomorphological map (1:25,000 scale) of the central sector of the Po Plain (northern Italy) are presented. The geomorphological map represents fluvial and anthropogenic landforms as well as the distribution of the textures of superficial alluvial deposits. It resulted from the integration of different study methods, including remote sensing data analysis, field surveys and grain size analysis of superficial deposits.

The micro-relief map was a fundamental tool for identifying many inconspicuous landforms. The geomorphological map can provide local authorities with useful information for correct territorial management and planning, in particular for seismic and flood hazard assessment.

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Geomorphological map; micro-relief map; Po Plain; Northern Italy; geodatabase

1. Introduction

The Po plain is the most extensive plain in Italy with a surface of approximately 46,000 km^2 and an average population density of 450 inhabitants/km^2. Main roads and highways cross it, with many urban centres and industrial settlements widely developed, while the rest of the plain is characterized by intensive farming activities. The production carried out in the plain and surrounding regions constitutes more than 50% of the Gross Domestic Product (GDP) of Italy (Marchetti, Soldati, & Vandelli, 2017).

The updated and large-scale geomorphological map of the central Po Plain is presented with the intent of laying the basis for territorial management and planning.

These geomorphological data are of paramount importance for the correct identification of areas susceptible to floods and areas that may be affected by liquefaction and other coseismic effects during earthquakes potentially threatening human lives and activities. This is particularly important for the areas struck by the seismic sequence of May 2012 which affected the central sector of the Po Plain. The sequence was dominated by two main events (Mw = 5.9 of May 20th and Mw = 5.8 of May 29th) that caused 27 deaths, over 400 persons injured, the evacuation of 14,000 people and considerable damage to houses, economic activities and cultural heritage. The environmental effects of the earthquakes mainly consisted of liquefaction-related phenomena such as sand boils or sand water ejections, ground cracks and soil subsidence (Di Manna et al., 2012; Emergeo, 2013; Ravazzi et al., 2013).

2. Geological and geomorphological outline of the study area

The Po Plain is located between the Alps and the Apennines (Figure 1). It was the foreland basin of the Northern Apennines and of the Southern Alps during the Paleogene (Turrini, Toscani, Lacombe, & Roure, 2016, and reference therein). The River Po, the longest watercourse of Italy (652 km) with a 74,970 km^2 wide catchment, flows eastward within a completely embanked meandering course, from the western Alps to the Adriatic Sea. In the central portion of the Po Plain, the Po abruptly turns northward between the provinces of Parma and Mantua (Figure 2).

Five physiographic units can be distinguished in the Po Plain (Figure 1; Marchetti, 2002), they are listed below in stratigraphic order.

(1) Holocene deposits in the central sector of the plain constitute the *Holocene Floodplain* unit, formed by aggradation of the River Po (Figure 3a) and its right tributaries. The *Holocene Floodplain* unit is found in the south-western, central and eastern sectors of the study area, on the left and right sides of the River Po (Figure 1).
(2) A less extensive surface is located near the Apennine boundary of the Po Plain. It is made up of a system of coalescent fluvial fans developing at the Apennine foothills, the so-called *Late Pleistocene bajada* unit, related to the great amount of sediments produced during the LGM (Marchetti, 2002);

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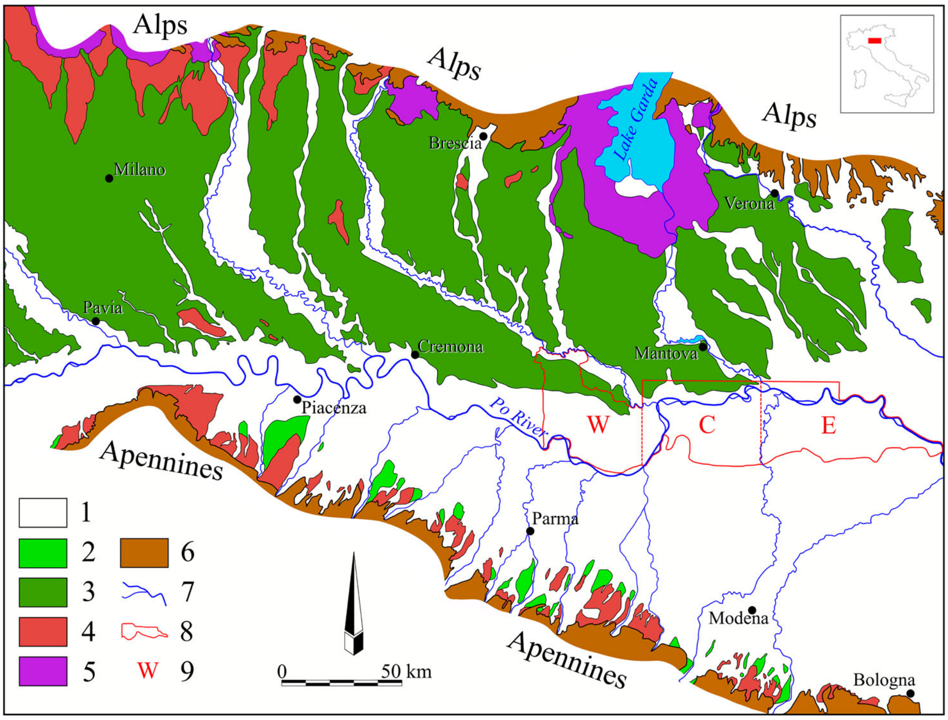

Figure 1 . The physiographic units of the Po Plain (modified after Marchetti, 2002). Legend: 1) *Holocene Floodplain* unit; 2) *Late Pleistocene bajada* unit; 3) *Main Level of the Plain* unit; 4) *old terraces* unit; 5) *glacial amphitheatres* unit; 6) bedrock; 7) hydrography; 8) study area; 9) geomorphological map subdivisions: western sector (W), central sector (C) and eastern sector (E).

(3) In the northern part of the Po Plain, adjacent to the glacial amphitheatres, the *Main Level of the Plain* unit has been identified (Marchetti, 2002). It consists of a complex of alluvial fans with their apex located on the Alpine foothill, coeval with the *Late Pleistocene bajada* unit, slightly inclined towards the River Po, made up of fluvioglacial and fluvial sediments. The latter were emplaced during the LGM, when rivers flowing from the Alps carried more water and sediment than today, as witnessed by abandoned riverbeds, which are oversized with respect to present-day hydrography (Marchetti, 1990). At present, the Alpine rivers flow in deep entrenched valleys carved into this unit because of

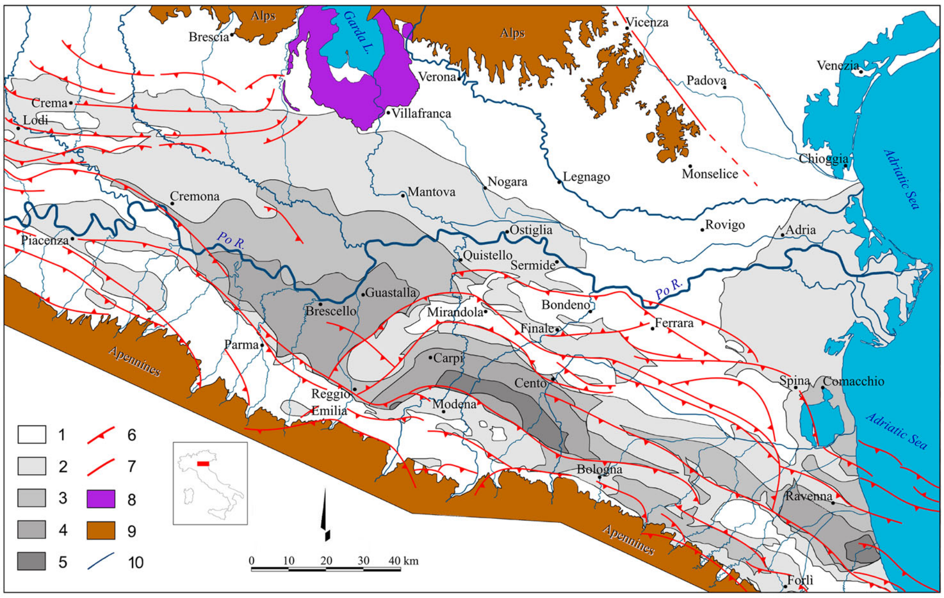

Figure 2 . Main structural lineaments and Quaternary sedimentary cover in the central and eastern Po Plain (modified after Ravazzi et al., 2013). The modern hydrographic network is represented together with the thickness of Pliocene-Quaternary sedimentary cover and the main tectonic elements. Legend: 1) Quaternary sedimentary cover <2 km; 2) Quaternary sedimentary cover from 2 to 4 km thick; 3) Quaternary sedimentary cover from 4 to 6 km thick; 4) Quaternary sedimentary cover from 6 to 8 km thick; 5) Quaternary sedimentary cover >8 km; 6) main overthrusts; 7) main faults; 8) glacial amphitheatres; 9) Alpine and Apennine reliefs; 10) main hydrography.

Figure 3. Examples of geomorphological features in the central Po Plain: (a) the River Po near Borgoforte (central sector of the Main Map); (b) fluvial ridge belonging to an abandoned Po stretch that was active in the Bronze Age south-west of Sermide (eastern sector of the Main Map); (c) Inundated Po highwater riverbed at San Benedetto Po due to the 2000 flood (central sector of the Main Map); (d) 2014 crevasse splay (lighter area) occurring in the Po highwater riverbed at San Matteo delle Chiaviche (central sector of the Main Map); (e) fluvial escarpment at the northern boundary of the *Main Level of the Plain* at Piadena (western sector of the Main Map); (f) abandoned Po riverbed (called 'Old River Po') active in Roman and Medieval times between Gonzaga and Pegognaga (eastern sector of the Main Map).

an intense erosional phase occurring during the Lateglacial. The southern boundary of the *Main Level of the Plain* is constituted by an escarpment resulting from fluvial erosion, due to the northward migration of the River Po during the Holocene. The *Main Level of the Plain* can be found in the north-western sector of the mapped area (Figure 1).

(4) At the margin of the Alps and Apennines, a series of fluvioglacial and fluvial terraces have been included in the *old terraces* unit. These terraces have rubified soils and polygenetic loess covers, which constitute the remnants of the ancient Po Plain surface, prior to the Last Glacial Maximum (LGM), they were isolated by intense erosional phases resulting from deglaciation (e.g. Marchetti, 2002).

(5) At the foothills of the Alps, the *glacial amphitheatres* unit is found. This physiographic unit includes moraines and valleys scoured by glaciers during the Pleistocene.

Extensive seismic reflection data, used for oil exploration (Pieri & Groppi, 1981) and further structural models (e.g. Ghielmi et al., 2010; Turrini et al., 2016), show the presence of two main compressive tectonic structures: the Pede-Apennine thrust front, in the foothills of the chain, and three buried arcs constituting the most advanced thrusts of the Apennine chain. The most active of these thrusts below the plain surface, named Ferrara Folds or Ferrara Arc, has a curved trend stretching beneath the towns of Reggio Emilia, Mirandola, Finale Emilia and Cento (Figure 2). The two earthquakes, occurring on 20th and 29th May 2012 (Mw = 5.9 and 5.8 Mw = respectively), which caused the uplift of 10–15 cm of the areas close to the epicentre, have been associated with the Ferrara folds (Bignami et al., 2012; Caputo et al., 2015). North of the River Po, the frontal part of the Southern Alps is buried under the Po Plain sediments and forms the Pede-Alpine homocline between Verona and Ostiglia (Figure 2).

The geomorphological evolution of the Po Plain has been mainly driven by tectonic uplift and climate change interplay. In particular, the activity of the Apennine thrusts has produced a generalized northward shifting of the River Po and its tributaries between Brescello and Ferrara (Figure 2) (Panizza & Castaldini, 1987; Vannoli, Burrato, & Valensise, 2014 and references therein). In fact, a large number of abandoned riverbeds, attributable to the River Po, have been recognized (e.g. Castiglioni et al., 1997; Castiglioni & Pellegrini, 2001, and references therein). In addition, climate change has caused significant sea level variations, which directly influence fluvial dynamics (e.g. Bruno, Piccin, Sammartino, & Amorosi, 2018). Anthropogenic activities, especially in past centuries, are an important factor modifying the landscape. In particular, fluvial and hydraulic interventions (such as meander cutting), channelization, quarrying activities, land use changes and deforestation have increased over time (Ravazzi et al., 2013).

3. Map overview

3.1. Methods

Remote sensing and altimetric terrain data, field surveys, sampling and grain size analysis of superficial deposits were used in order to interpret and map the geomorphological features of the study area.

Remote sensing interpretation has been fundamental for identifying landforms with reliefs higher than one metre and with shapes delimited by surfaces with very different slope angles, such as fluvial scarps and V-shaped valleys. The remote sensing dataset included: i) aerial photos at the analogic scales of 1:33,000 (IGMI, 1955), 1:20,000 (Lombardy Region, 1981) and 1:70,000 (CGR, 1994); ii) multitemporal ortho-photos (since 2000) available on-line on the Italian National Geoportal website http://www.pcn.minambiente.it/viewer/; iii) high-resolution satellite images published by Google Earth and ranging from 2003 to 2018. The main geomorphological features identified with these remote sensing data were then verified in the field. Geomorphological field surveys and mapping were performed at 1:5,000 scale, investigating near surface deposits and landforms (e.g. fluvial ridges, crevasse splays) The terminology, symbology and landform classification criteria mainly follow the ones used in the Geomorphological Map of the Po Plain by Castiglioni et al. (1997).

Field and laboratory grain size analyses were carried out on sediment samples collected at a depth of 0.5–1 m. The number of samples is between 4 and 8 per km^2, depending on the particle size homogeneity of the identified geomorphological features. In particular, quick grain size assessments in the field was performed on the collected samples following the procedure described by Gasperi and Gelmini (1976) and in laboratory by means of sieving and settling standard techniques.

Remote sensing data analysis has been integrated with micro-relief investigations, which enable to represent the landforms at a greater detail. The micro-relief map has been calculated by interpolation of contour lines at 1 m intervals, drawn on the basis of the terrain altimetry data of the Regional Technical Map (CTR) at a 1:10,000 scale (Lombardy Region, 1981).

All remote sensing, fieldwork and laboratory data have been stored in a spatial database and processed by means of a Geographic Information System (GIS) in order to obtain the maps described in the following sections.

3.2. Micro-relief map

Micro-relief analysis has proved to be a fundamental tool in the elaboration of the geomorphological map (cf. Section 3.3) and useful for outlining many inconspicuous landforms (e.g. fluvial ridges, Figure 3b).

The micro-relief map shows that in the north-western sector of the study area the topographic surface consists of a gentle south-south-eastward dipping plain at 20–30 m a.s.l., which is the top of the *Main Level of the Plain* unit (cf. Section 2). This surface has an average slope of about 0.08% and is crossed by a series of north-south V-shaped small valleys.

A change in topography in the south of the western sector, occurring along a small scarp, marks the northern boundary of the *Holocene Floodplain* unit, characterized by a gentler (0.03% average slope) eastward dipping surface at 25–17 m a.s.l. At the south-western end of the central sector, the elevation of the alluvial plain slightly increases, defining an east-west fluvial ridge hosting some of the main urban settlements (e.g. Casalmaggiore and Viadana).

Further to the east, the micro-relief map shows lower altitudes of the *Holocene Floodplain* unit, ranging from 20 to 21 m a.s.l. near Suzzara and Gonzaga, to 6–7 m a.s.l. at the eastern end of the study area near Felonica. This gentle, eastward sloping sector of the alluvial plain (average slope of 0.03%) corresponds to the 'Oltrepò Mantovano' (the area of Mantua province south of the R. Po) and is crossed by mainly sinuous east-west fluvial ridges, along large depressions, clearly identifiable in the micro-relief map.

3.3. Geomorphological map

The geomorphological map at a 1:25,000 scale has been divided into three sectors (western, central and eastern) and includes the hydrographic network, fluvial landforms, anthropogenic landforms and texture of superficial alluvial deposits.

3.3.1. Hydrographic network

The main elements of the hydrographic network are the River Po, flowing from west to east, its left tributaries, the Rivers Oglio (western and central sector) and Mincio (central and eastern sector) flowing from the Alps, and the River Secchia (eastern sector), a right tributary flowing from the Apennines. The western and eastern stretches of the Po are sinuous and slightly sinuous; in the central part the river shows an evident northward bend near Dosolo determined by river diversions occurring in the eighth century BCE and twelveth century CE (Castaldini, 1989).

The Po is hanging inside areas subject to river flooding in correspondence with highwater beds that reach a width of more than 2 km. The highwater beds are located between a system of outer main river embankments that can be 5–6 m higher than the surrounding plain. The abundant solid load accumulated since the mid-Holocene up to the 1950s mainly determined the hanging of the Po riverbed over the plain, which was favoured by the constriction of the river within a system of embankments implemented since Roman times (Marchetti et al., 2017). Between the 1960s and 1970s, the Po began to erode its own alluvial sediments, causing a deepening of its bed (Marchetti, 2002). The sector is also crossed by a dense network of totally or partially artificial irrigation canals. Worthy of notice for their significant dimensions, are the man-made canals located to the south of the confluence between the Rivers Oglio and Po (central sector). Near this area, both natural and artificial ponds, with sub-circular or elongated shapes, are present in correspondence with highwater bed areas. These features outline abandoned riverbeds and highwater bed channels (cf. section 3.3.2); the sub-circular ones can be related to piping phenomena occurring during floods (e.g. Pellegrini & Castaldini, 2008). Various rectangular artificial ponds, mainly in the depressed areas, are also found on the western and eastern side of the area.

3.3.2. Fluvial landforms

Important features in the map are crevasse splays, which bear witness to the occurrence of bank breaches and floods in space and time. They were mapped as active those occurred after the year 2000 CE, when the latest major highwater event affecting the River Po occurred (Figure 3c).

Inactive crevasse splays were identified all along the Po embankments and in correspondence with the relict fluvial ridges located on its right side (central and eastern sector of the Main Map). Worthy of notice are the inactive crevasse splays located on relict fluvial ridges between Suzzara and Pegognaga, and near Motteggiana, which are located on the outer side of the former meanders, where stream flow was inferred to have been higher.

Numerous inactive crevasse splays were mapped along the River Po testifying floods occurring in historical times along the investigated river stretch, as reported in literature (e.g. Autorità di Bacino del Fiume Po, 2014; Castiglioni & Pellegrini, 2001; Govi & Turitto, 2000; Luino, 2013).

Two active crevasse splays were mapped within the inner part of the highwater bed, west of San Benedetto Po (northeastern part of the central sector). Both originated from the 2000 overflow (Marchetti, 2008). Another active crevasse splay was mapped east of San Matteo delle Chiaviche (western part of the central sector), which originated during the 2014 Po overflow (e.g. Zanichelli, Pavan, Pecora, & Ricciardi, 2015; Figure 3d).

V-shaped valleys were mapped in the north-western part of the area. These valleys, carved at the escarpment of the *Main Level of the Plain* unit (Figure 3e), were formed by the erosive action of the hydrographic network formed after the Last Glacial Maximum glacier retreat, and evolved by northwards regressive erosion (Castiglioni & Pellegrini, 2001; Cremaschi & Marchetti, 1995).

In the mapped area there are extensive traces left by the relict hydrographic network, in the form of abandoned riverbeds at the plain level or slightly below.

On the *Main Level of the Plain*, the traces of abandoned riverbeds have a north-south direction and low continuity; they are slightly sinuous and often slightly recessed within the surrounding plain.

The most striking geomorphological features on left side of the River Po (western and central sectors) are the numerous, close and intersecting traces of abandoned riverbeds at the plain level or slightly below. Flow directions of these paleo-channels, corresponding to ancient traces of the River Po, were generally oriented from west to east. On the right side of the River Po (central and eastern sectors), the traces of abandoned riverbeds at plain level or slightly below are clearly outlined. Among them, worthy of notice are the abandoned meandering riverbeds between the River Po and Suzzara and Pegognaga, originating between the twelveth and sixteenth centuries CE (Castaldini, 1989).

Fluvial ridges, related to the abandoned hydrographic network, are the most common geomorphological features of the area on the right side of the River Po (within the central and eastern sectors). The west-east meandering fluvial ridges between the River Po, Suzzara and Pegognaga and the fluvial ridges with approximate meandering south to north direction, on the left side of the River Secchia, are linked to the fluvial dynamics of an ancient River Po path that was active between the Roman period and the Late Middle Ages (Figure 3f). Today it corresponds to a secondary stream called ‘Po Vecchio’ which means ‘Old Po’ (Castaldini, 1989).

On the right side of the River Secchia (eastern sector) discontinuous fluvial ridges with west-east direction are found. They are related to the fluvial dynamics of an ancient Po branch active during the Bronze Age. In the same area, a continuous fluvial ridge was mapped crossing the locality of San Giacomo delle Segnate and dividing near Poggio Rusco. This fluvial ridge is one of the ancient courses of the River Secchia, which started following its present path after the fourteenth-fifteenth century CE (Castaldini, 1989).

Channels within the main embankments inside the highwater bed, occasionally occupied by the River Po during overflow events, were mapped as highwater bed channels.

A few depressions were mapped by means of the micro-relief map; they are located south of the fluvial escarpment at the northern boundary of the *Holocene Floodplain* unit. A large depressed area, corresponding to an interfluvial basin, is located between San Matteo delle Chiaviche and Bugno di Cavallara, on the left-hand side of the Po riverbed. Another depressed area is located north-east of the confluence between the Rivers Oglio and Po, around an extensive crevasse splay.

On the left side of the River Secchia, the depressed areas are numerous but not extensive and they are bounded by fluvial ridges. The largest depressed area, with a north-south axis, is located between San Benedetto Po and Moglia and is split in two by a large reclamation channel, which was built inside embankments following the same axis as the depressed area. Extensive depressions, located on the right side of the River Secchia, attain a minimum elevation of 6–7 m a.s.l. These depression areas are the traces of the presence – from the Middle Ages to the 1900s – of extensive marshes, later reclaimed (cf. Marchetti et al., 2017).

Among river erosional features, in addition to V-shaped valleys, it was also possible to recognize fluvial scarps. The active ones are limited to highwater beds along the River Po. Evident from the micro-relief map are: a) the north-facing fluvial scarp located on the right side of the River Oglio (northern part of the western sector) bordering the *Main Level of the Plain* towards the north and b) the fluvial scarps, partially remodelled by man, bordering to the south the *Main Level of the Plain*. Worthy of note is the slope identified in correspondence with the abandoned riverbed between Sabbioneta and Commessaggio. The environmental co-seismic effects induced by the 2012 seismic sequence, as well as the damage to structures and infrastructures, appeared concentrated and aligned along specific patterns. Their spatial distribution was mostly controlled by the presence of paleo-riverbeds, highwater bed channels and crevasse splays of the main rivers crossing the epicentral area. In particular, the most affected zones in the study area were near the River Secchia and the villages of Quistello (Figure 4a) and Moglia (Figure 4b).

3.3.3. Texture of alluvial superficial deposits

In the investigated area, superficial deposits are those located at depths varying from 0.5 to 1 m, that are immediately below the layer affected by paedogenesis and modified by agricultural practices. The superficial textures of the deposits are influenced by the same processes that originated the Po Plain.

Surface deposits have been classified by their texture: i) mainly sandy deposits (sand > 40%); ii) mainly silty deposits (silt > 40%); iii) mainly clayey deposits (clay > 40%). Only one peat deposit was found to the east of the village of Calvatone.

Spatial alternations of sandy and silty deposits characterize the northern part of the western sector, which corresponds to the *Main Level of the Plain*. These superficial deposits were interpreted as the distal portions of megafans created by intense sedimentation during the LGM (Marchetti, 2002).

The area on the left side of the River Po (western and central sectors) is mainly characterized by a uniform cover of silty and clayey deposits emplaced by recurrent flooding of the River Po (e.g. Castiglioni & Pellegrini, 2001; Luino, 2013). There are extensive areas consisting of mainly clayey deposits between Vicomoscano and

Figure 4. Examples of liquefaction induced by the earthquake of 29th May 2012 in the surroundings of Quistello (a) and in the urban centre of Moglia (b), respectively within the eastern and central sectors of the Main Map.

San Matteo delle Chiaviche, north of Sabbioneta and in correspondence with Commessaggio.

Between Martignana di Po and Viadana, the area is characterized by a certain variability of textures conditioned by many abandoned riverbeds at plain level or slightly below and by fine sediments left by the recurring floods of the Po.

On the right side of the River Po (central and eastern sectors) the textural distribution depends on the presence of traces of the abandoned hydrography. Mainly sandy deposits can be found in correspondence with fluvial ridges, abandoned riverbeds at the plain level or slightly below and crevasse splays. Mainly silty deposits prevail in the sector on the left side of the River Secchia and they are located along the traces of relict hydrography. Mainly clayey deposits prevail on the right side of the River Secchia. Their origin can be attributed to the main flooding events occurring up to the nineteenth century in the lowland areas of the provinces of Mantua, Modena and Ferrara (Castiglioni & Pellegrini, 2001; Luino, 2013).

3.3.4. Anthropogenic landforms

In the mapped area, anthropic interventions have played a considerable role in the modification of the hydrographic network, mainly owing to the construction of levees, artificial canals for reclamation or for agricultural/industrial water provision and bank protection structures. The levees systems relevant to the investigated stretches of the rivers Po, Oglio, Mincio and Secchia are depicted in the geomorphological map.

The anthropic influence over the study area is also due to the progressive spreading of urban centres. By comparing the current extension of urban settlements with those of the past, inferred from multi-temporal aerial photographs, it can be assumed that the biggest urban development took place after the 1950s.

Past and almost abandoned quarrying activities also produced landscape changes. While in the past the quarrying activities were developed all over the plain, at present, the extraction of aggregates affects only the Po riverbed. The active quarry areas are confined in the highwater beds of the River Po and are represented by screening plants (Castaldini, Giusti, & Marchetti, 2003). In the geomorphological map, quarries with a dry bottom are those in which excavation has not reached the water table. Reclaimed quarries were largely turned into agricultural fields, masking the former use of the area.

4. Conclusions

The maps presented in this paper provide a comprehensive representation of the landscape features of the central Po Plain.

The geomorphological map shows the following features:

(a) elements characterizing present-day hydrographic network (hydrography, highwater beds, ponds);
(b) alluvial landforms (e.g. abandoned riverbeds, fluvial ridges, crevasse splays) which are representative of fluvial evolution over time;
(c) spatial distribution of texture of superficial deposits, distinguished in four classes: mainly sandy, silty, clayey and peat deposits;

(d) anthropogenic landforms (quarries, bank protection structures, main levees, etc.) from which it can be perceived how strong the anthropogenic imprint has been on the landscape.

This geomorphological map is an important tool for land use policy, geological hazard assessment and development of specific civil protection plans, with particular reference to fluvial and peri-fluvial environments exposed to flood-related hazards.

In addition, as previously stated, liquefaction and other environmental co-seismic effects caused by the two earthquakes that affected the central Po Plain in May 2012 have highlighted that hazardous phenomena were concentrated along paleo-hydrographic features (e.g. Emergeo, 2013). In conclusion, the geomorphological and textural data reported in the maps provide public boards with fundamental information for the subsequent assessment and reduction of seismic- and flood-related risks.

Software

Cartographic data are stored in a personal geodatabase and the final maps were produced in ESRI ArcMap 10.1.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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